

Deciphering the properties of hot and dense matter with hadron-hadron correlations

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Abstract

Two classes of jet correlations in hot and dense matter are explored. Correlations between very high transverse momentum hadrons within a jet sample the gluon density of the medium, where, the minimal modification on the same side as the trigger is consistent with the picture and parameters of partonic energy loss. Lower momentum partons, sampled through softer correlations, due to their larger wavelengths are sensitive to the presence of composite structures in the medium. Scattering off such states may modify the dispersion relation of the radiated gluons resulting in conical patterns in the detected correlations.

Key words: Jet Correlations, Quark Gluon Plasma, Cherenkov radiation

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1 Introduction

Ultra-relativistic collisions of heavy nuclei lead to the production of highly excited strongly interacting matter [1]. Present day collisions at the Relativistic Heavy-Ion Collider (RHIC) have yielded numerous startling observables; all of which point to the production of matter which is decidedly non-hadronic and possibly deconfined in nature [2]. One of the primary signatures for non-hadronic behaviour is the collective nature of the matter, different from that observed in excited hadronic media created at lower energy colliders. Yet another observable is the opacity of the produced matter to the passage of hard jets through it [3]. It is indeed the large observed suppression of the single inclusive spectrum of high transverse momentum (p_T) hadrons that has yielded the estimate that the produced matter is 30 times as dense as normal nuclear matter. Such estimates are based on the picture of partonic energy loss. In the first part of these proceedings, this mechanism is tested via the modification of the correlation between two high p_T hadrons within the same jet.

Very high momentum partons and radiated hard gluons [4], selectively sampled through the observation of high transverse momentum hadrons (referred to as hard-hard correlations) [5,6], tend to sample the partonic substructure of the medium. As a result, any formalism that reproduces the single inclusive spectrum must also be able to estimate the modified correlation between hadrons produced in the fragmentation of a single jet.

The observed collective behaviour of the produced matter, manifested in its radial and elliptic flow is, oddly enough, different from what would have been expected from perturbative QCD calculations, assuming a quasi-particle picture of the quark gluon plasma (QGP). This raises the question as to what are the prevalent degrees of freedom in the produced matter. There exist conjectures that such matter is composed of a tower of bound states of quasi-particle quarks and gluons [7]. In the second part of these proceedings we explore the possibility that softer gluons radiated from hard partons, due to their longer wavelengths, are influenced by such states in the medium. This modifies the dispersion relation of the gluons [8,9,10,11] leading to non-jet-like correlations between a high momentum hadron and a softer hadron (referred to as hard-soft correlations) [12,13].

2 Hard-Hard correlations

We commence with a study of the correlations between two hard particles on the same side. Such two-hadron correlations have been measured both in Deep-Inelastic Scattering (DIS) off large nuclei [14] and in high-energy heavy-ion collisions [5]. Within the energy ranges and angles explored, it is most likely that both these particles have their origin in a single jet which is modified by its interaction with the medium. Hence, such analysis requires the introduction of a dihadron fragmentation function ($D_q^{h_1 h_2}$) [15], which accounts for the number of pairs of particles fragmenting from a jet. In the case of modification in cold nuclear matter, a nucleus A with forward momentum Ap^+ , and a quark structure function $f_q^A(x_B, Q^2)$ is struck with a virtual photon with four-momentum $q \equiv [-Q^2/2q^-, q^-, \vec{0}_\perp]$. The modified dihadron fragmentation function, for the production of two hadrons (h_1, h_2 , off the struck quark) with momentum fractions z_1, z_2 , is calculated as,

$$\begin{aligned} \tilde{D}_q^{h_1, h_2}(z_1, z_2) = & D_q^{h_1, h_2}(z_1, z_2) + \int_0^{Q^2} \frac{dl_\perp^2}{l_\perp^2} \frac{\alpha_s}{2\pi} \left[\int_{z_1+z_2}^1 \frac{dy}{y^2} \left\{ \Delta P_{q \rightarrow qg}(y, x_B, x_L, l_\perp^2) \right. \right. \\ & \times D_q^{h_1, h_2} \left(\frac{z_1}{y}, \frac{z_2}{y} \right) + \Delta P_{q \rightarrow gq}(y, x_B, x_L, l_\perp^2) D_g^{h_1, h_2} \left(\frac{z_1}{y}, \frac{z_2}{y} \right) \left. \right\} \end{aligned} \quad (1)$$

$$+ \int_{z_1}^{1-z_2} \frac{dy}{y(1-y)} \Delta \hat{P}_{q \rightarrow qg}(y, x_B, x_L, l_\perp^2) D_q^{h_1} \left(\frac{z_1}{y} \right) D_g^{h_2} \left(\frac{z_2}{1-y} \right) + (h_1 \rightarrow h_2) \Big].$$

In the above, $x_B = -Q^2/2p^+q^-$, $x_L = l_\perp^2/2p^+q^-y(1-y)$, l_\perp is the transverse momentum of the radiated gluon, $\Delta P_{q \rightarrow qg}$ and $\Delta P_{q \rightarrow gq}$ are the modified splitting functions with momentum fraction y , whose forms are identical to that in the modified single hadron fragmentation functions [16]. The switch ($h_1 \rightarrow h_2$) is only meant for the last term, which represents independent fragmentation of the quark and gluon after the induced bremsstrahlung. The corresponding modified splitting function is,

$$\Delta \hat{P}_{q \rightarrow gq} = \frac{1+y^2}{1-y} \frac{C_A 2\pi\alpha_s T_{qg}^A(x_B, x_L)}{(l_\perp^2 + \langle k_\perp^2 \rangle) N_c f_q^A(x_B, Q^2)}, \quad (2)$$

($\Delta P_{q \rightarrow qg}$ is similar in form but also contains contributions from virtual corrections). In the above, $C_A = 3$, $N_c = 3$, and $\langle k_\perp^2 \rangle$ is the average intrinsic parton transverse momentum inside the nucleus. Note that both modified splitting functions depend on the quark-gluon correlation function T_{qg}^A in the nucleus (see Refs. [17] for detailed expressions) which also determines the modification of single hadron fragmentation functions. As a result, no additional parameters are required. Due to the existence of sum rules connecting dihadron fragmentation functions to single hadron fragmentation functions (D_q^h) [15], one studies the modification of the conditional distribution for the second rank hadrons, $R_{2h}(z_2) \equiv \int dz_1 D_q^{h_1, h_2}(z_1, z_2) / \int dz_1 D_q^{h_1}(z_1)$.

In high-energy heavy-ion (or $p+p$ and $p+A$) collisions, jets are always produced in back-to-back pairs. Correlations of two high- p_T hadrons in azimuthal angle generally have two Gaussian peaks [5,6]. The integral of the near-side peak (after background subtraction) over the azimuthal angle can be related to the associated hadron distribution or the ratio of dihadron to single hadron fragmentation functions. In these experiments, one usually considers the integrated yield of hadrons [over a range of transverse momentum (p_T^{assoc}) associated with a trigger hadron of higher momentum (p_T^{trig}) *i.e.*,

$$R_{2h} = \int dp_T^{\text{assoc}} \frac{d\sigma^{AB}}{dy dp_T^{\text{trig}} dp_T^{\text{assoc}}} \Big/ \frac{d\sigma^{AB}}{dy dp_T^{\text{trig}}}. \quad (3)$$

Estimations of the associated yields require a calculation where two hadrons with a given p_T^{trig} and p_T^{assoc} will originate from a wide range of initial jet energies weighted by the initial hard cross sections (obtained via a convolution of the initial structure functions and hard partonic cross sections [17,18]). Assuming factorization of initial and final state effects, the differential cross-section for the production of two high p_T hadrons at midrapidity from the

impact of two nuclei A and B at an impact parameter between b_{min} , b_{max} is given as,

$$\frac{d\sigma^{AB}}{dydp_T^{\text{trig}}dp_T^{\text{assoc}}} = \int_{b_{min}}^{b_{max}} d^2b \int d^2r t_A(\vec{r} + \vec{b}/2) t_B(\vec{r} - \vec{b}/2) \times 2K \int dx_a dx_b G_a^A(x_a, Q^2) G_b^B(x_b, Q^2) \frac{d\hat{\sigma}_{ab \rightarrow cd}}{d\hat{t}} \tilde{D}_c^h(z_1, z_2, Q^2), \quad (4)$$

where, $G_a^A(x_a, Q^2) G_b^B(x_b, Q^2)$ represent the nuclear parton distribution functions to find a parton $a(b)$ with momentum fractions $x_a(x_b)$ in a nucleus $A(B)$, t_A (and t_B) represents the nuclear thickness function and $d\hat{\sigma}_{ab \rightarrow cd}/d\hat{t}$ represents the hard parton cross section with the Mandelstam variable \hat{t} . The factor $K \simeq 2$ accounts for higher order corrections and is identical to that used for the single hadron cross sections. The medium modified dihadron fragmentation function may be expressed as in Eq. (1), with the modified splitting functions generalized from Eq. (2) to the case of heavy-ion collisions.

The associated hadron correlation is found slightly suppressed in DIS off a nucleus versus a nucleon target and moderately enhanced or unchanged in central $Au + Au$ collisions relative to that in $p + p$ (in sharp contrast to the observed strong suppression of single inclusive spectra in both DIS and central $A + A$ collisions [19,3]). Shown in the left panel of Fig. 1 is the predicted ratio of the associated hadron distribution in DIS off a nuclear target (N and Kr) to that off a proton, as compared to the experimental data from the HERMES collaboration at DESY [14]. The suppression of the associated hadron distribution $R_{2h}(z_2)$ at large z_2 due to multiple scattering and induced gluon bremsstrahlung in a nucleus is quite small compared to the suppression of the single fragmentation functions [19,20]. The effect of energy loss seems to be borne, mainly, by the leading hadron spectrum.

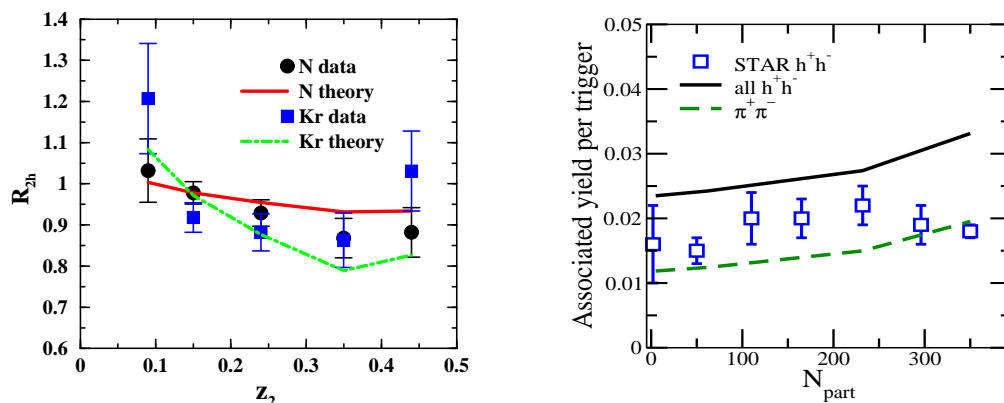


Fig. 1. Results of the medium modification of the associated hadron distribution in a cold nuclear medium versus its momentum fraction (left panel) and versus system size in a hot medium (right panel) as compared to experimental data (see text for details).

Computations of the associated yield in a heavy-ion collision, as a function of the number of participants (N_{part}) are plotted in the right panel of Fig. 1 along with experimental data from Ref. [6]. In this plot, p_T^{trig} ranges from 8–15 GeV while the associated momentum ranges from $6 \text{ GeV} < p_T^{\text{assoc}} < p_T^{\text{trig}}$. Unlike the case in DIS (left panel), the data are *not* normalized by the associated yield in $p+p$ collisions. As a result, the normalization is sensitive to the flavour content of the detected hadrons. The experimental results include all charged hadrons (with certain decay corrections [6]), whereas the theoretical predictions include two extreme possibilities: the lower dashed line denotes charged pions (π^+, π^-) inclusive of all decays and the upper solid line denotes p, \bar{p}, K^+, K^- and π^+, π^- inclusive of all decays. The two cases bracket the experimental data, lending support to the framework of partonic energy loss. Decay corrections, which essentially involve removing contributions from unstable particle decays to the detected flavour content, will slightly reduce the plotted associated yields.

While no trend may be discerned from the experimental measurements, the theoretical predictions show a slight enhancement with centrality due to increased trigger bias in more central collisions. In central $Au + Au$ collisions, triggering on a high p_T hadron biases toward a larger initial jet energy and therefore smaller z_1 and z_2 . This is in contrast to the rise in the effective z in the single inclusive estimates of Ref. [20]. In such observables there is no triggering on the p_T of the leading hadron and hence no bias of the initial parton energy. This effect of trigger bias leads to an enhancement in the associated yield due to the shape of dihadron fragmentation functions [15].

An alternate explanation for the near constant associated yield as a function of centrality has been that of pure surface emission. In an extreme example of this view, one outlines a superficial annular ring in the transverse plane of a central heavy-ion collision. All partons produced on this outer annulus escape unmodified, while all partons produced in the region enclosed by the annulus are completely quenched and do not escape the dense system regardless of their energy. This view is somewhat naive, as higher momentum partons will naturally sample deeper into the medium. In the results presented above no such constraint on the production points has been assumed. The agreement between the theoretical predictions and experimental results for the associated yield are thus highly non-trivial.

3 Hard-Soft correlations

For triggered events in central heavy-ion collisions, the Gaussian peak associated with the distribution of high p_T associated particles on the away side is almost absent. As the p_T of the associated particle is reduced, curious patterns emerge on the away side. A double humped structure is seen: Soft hadrons cor-

related with a quenched jet have a distribution that is peaked at a finite angle away from the jet [12,13], whereas they peak along the jet direction in vacuum. The variation of the peak with the centrality of the collision indicates that this is not due to the destructive interference of the LPM effect. One proposal has been that the energy deposited by the away side jet excites a density wave in the medium which leads to a Mach cone like structure [10,11]. In these proceedings an alternate possibility will be explored.

As pointed out in the introduction, the observed collective flow requires that the produced matter be strongly interacting [21], with a very low viscosity [22]. There already exists a candidate model for such matter, consisting of a tower of colored bound states of heavy quasi-particulate quarks and gluons [7]. This model has however not fared well in comparison to lattice susceptibilities [23], which rule out the possible existence of such bound states in the quark sector. Such calculations on the lattice do not, however, constrain the gluon sector of the plasma which may contain such states. It may indeed be possible for bound states to interact with gluons radiated by a hard parton passing through the dense matter.

The existence of coloured bound states in a deconfined plasma along with the assumption that these bound states have excitations which may be induced by the soft gluon radiated from a jet, allows for a large index of refraction. If the energy of the gluon is smaller than that of the first excited state, the scattering amplitude is attractive. As a result, the gluon dispersion relation in this regime becomes space-like ($\epsilon > 1$) and Cherenkov radiation will occur [8,24]. This is simply demonstrated in a Φ^3 theory at finite temperature with three fields: ϕ a massless field representing the gluon and two massive fields Φ_1 and Φ_2 with masses m_1 and m_2 in a medium with a temperature T (see Ref.[8] for details). The Lagrangian for such a system, ignoring the self-interactions between the scalars, has the form

$$\mathcal{L} = \sum_{i=1}^2 \frac{1}{2}(\partial\phi_i)^2 + \frac{1}{2}(\partial\Phi)^2 + \sum_{i=1}^2 \frac{1}{2}m_i^2\phi_i^2 + g\Phi\phi_2\phi_3. \quad (5)$$

The coupling constant g is dimensionful; this along with all other scales will be expressed in units of the temperature. Ignoring issues related to vacuum renormalizability of such a theory, we focus on a study of the dispersion relation of the massless scalar in such an environment. The thermal propagator of Φ in the interacting theory is given in general as $D(p^0, \vec{p}) = [(p^0)^2 - |\vec{p}|^2 - \Pi(p^0, \vec{p}, T)]^{-1}$, and the dispersion relation is given by the on-shell condition: $(p^0)^2 - |\vec{p}|^2 - \Pi(p^0, \vec{p}, T) = 0$. Here, $\Pi(p^0, \vec{p}, T)$ is the thermal self-energy of Φ due to loop diagrams such as the one shown in Fig.2.

The resulting dispersion relations of the ϕ field for different choices of masses

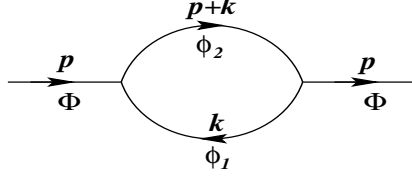


Fig. 2. General contribution to the self-energy of Φ due to transitional interaction.

of Φ_1, Φ_2 are shown in Fig. 3 along with the corresponding Cherenkov angles of the radiation in the right panels. We obtain a space-like dispersion relation at low momentum which approaches the light-cone as the momentum of the gluon (p^0, p) is increased. The variation of the corresponding angles may be actually detectable in current experiments. Even though we have studied a simple scalar theory, the attraction leading to Cherenkov-like bremsstrahlung has its origin in resonant scattering. Thus, the result is genuine and only depends on the masses of the bound states and their excitations. Further experimental and theoretical investigations into such correlations may allow for a possible enumeration of the degrees of freedom in the produced excited matter.

4 Conclusions

In these proceedings, the analysis of the properties of dense matter using the tool of jet correlations has been extended. Correlations between two high momentum hadrons within the same jet constitute an essential consistency check of the methodology and parameters of partonic energy loss. Correlations between a high momentum trigger and softer particles on the away side are shown to be more sensitive to the properties of the dense matter and the prevalent degrees of freedom. Work supported by the U.S. Department of Energy under grant nos. DE-FG02-05ER41367 and DE-AC03-76SF00098.

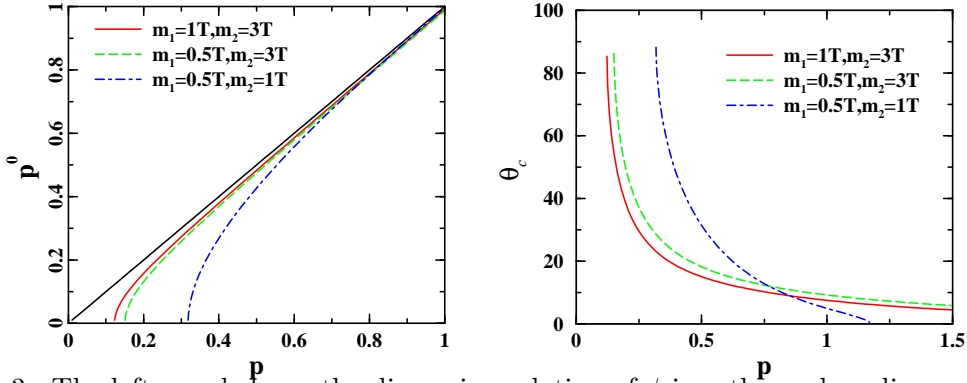


Fig. 3. The left panel shows the dispersion relation of ϕ in a thermal medium with transitional coupling to two massive particle. The right panel shows the corresponding Cherenkov angles versus the three momentum of the gluon.

References

- [1] P. Jacobs and X. N. Wang, Prog. Part. Nucl. Phys. **54** (2005) 443.
- [2] I. Arsene *et al.*, Nucl. Phys. A **757**, 1 (2005); B. B. Back *et al.*, *ibid.* **757**, 28 (2005); J. Adams *et al.*, *ibid.* **757**, 102 (2005); K. Adcox *et al.*, *ibid.* **757**, 184 (2005).
- [3] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 022301 (2002); C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **89**, 202301 (2002).
- [4] M. Gyulassy, I. Vitev, X. N. Wang and B. W. Zhang, arXiv:nucl-th/0302077.
- [5] C. Adler *et al.*, Phys. Rev. Lett. **90** (2003) 082302; S. S. Adler *et al.*, Phys. Rev. C **71** (2005) 051902.
- [6] J. Adams *et al.* [STAR Collaboration], arXiv:nucl-ex/0604018.
- [7] E. V. Shuryak and I. Zahed, Phys. Rev. D **70** (2004) 054507
- [8] V. Koch, A. Majumder and X. N. Wang, Phys. Rev. Lett. **96**, 172302 (2006).
- [9] A. Majumder and X. N. Wang, Phys. Rev. C **73**, 051901 (2006).
- [10] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, arXiv:hep-ph/0602183.
- [11] J. Ruppert and B. Muller, Phys. Lett. B **618**, 123 (2005).
- [12] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **95**, 152301 (2005)
- [13] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **97**, 052301 (2006)
- [14] P. Di Nezza, J. Phys. G **30**, S783 (2004).
- [15] A. Majumder and X. N. Wang, Phys. Rev. D **70** (2004) 014007; **72** (2005) 034007.
- [16] X. F. Guo and X. N. Wang, Phys. Rev. Lett. **85**, 3591 (2000); X. N. Wang and X. F. Guo, Nucl. Phys. A **696**, 788 (2001).
- [17] A. Majumder, E. Wang and X. N. Wang, arXiv:nucl-th/0412061.
- [18] A. Majumder, arXiv:nucl-th/0608043.
- [19] A. Airapetian *et al.*, Eur. Phys. J. C **20**, 479 (2001); Phys. Lett. B **577**, 37 (2003).
- [20] E. Wang and X. N. Wang, Phys. Rev. Lett. **89**, 162301 (2002).
- [21] M. Gyulassy and L. McLerran, Nucl. Phys. A **750**, 30 (2005)
- [22] D. Teaney, Phys. Rev. C **68**, 034913 (2003) [arXiv:nucl-th/0301099].
- [23] V. Koch, A. Majumder and J. Randrup, Phys. Rev. Lett. **95**, 182301 (2005)
- [24] I. M. Dremin, JETP Lett. **30**, 140 (1979); Nucl. Phys. A **767**, 233 (2006).